Relationship between fluidity and stability of self-consolidating mortar incorporating chemical and mineral admixtures

Nicolas Ali Libre*, Rahil Khoshnazar, Mohammad Shekarchi

Construction Materials Institute (CMI), School of Civil Engineering, University of Tehran, Tehran, Iran

ARTICLE INFO

Article history:
Received 4 August 2009
Received in revised form 22 November 2009
Accepted 3 December 2009
Available online 6 January 2010

Keywords:
Self-consolidating mortar
Admixtures
Fluidity
Stability
Viscosity

ABSTRACT

In this study, the effect of chemical and mineral admixtures, including superplasticizer, viscosity modifying agent (VMA), limestone powder and fly ash in different W/C on fluidity, viscosity, and stability of self-consolidating mortar is investigated and proper workability regions for the prepared mixtures are presented. The obtained results indicate that W/C is the most significant parameter influencing the rheological properties of cementitious mixtures, specially their stability. Furthermore, the maximum allowable W/C for preventing inhomogeneity could not be a fixed value for all the mixtures and should be adjusted for the target fluidity. On the other hand, using VMAs is an effective method for stabilizing self-consolidating mortars and preventing any kinds of instability while limestone powder and fly ash mainly affect bleeding and aggregate blockage. Besides, these mineral admixtures improved the fluidity of the mixtures to some extent.

© 2009 Elsevier Ltd. All rights reserved.

1. Introduction

Achievement of a super workable concrete, which could be cast easily without any signs of instability, has been desired by engineers for the last decades [1–4]. Increasing the fluidity of concrete is considered as the first step of assessing extreme workability and may govern by its water content or by the chemical and mineral admixtures. However, high fluidity of such mixtures does not lead to excellent workability in all cases and can eventually promote some instability during transportation, placement, compaction and/or finishing. Instability can occur in various forms such as bleeding, coarse aggregate settlement and blocking [5] during flow across narrow sections and densely reinforced members. Bleeding, which is concerned with water migration, describes an internal and a surface bleeding. Surface bleeding takes place when water migrates to the surface and internal bleeding occurs inside the mixture when the embedded bars are surrounded by water. Bleeding and settlement can weaken the quality of the interface between aggregate and cement paste with direct bearing on impermeability and mechanical properties [6]. The bond of cement paste and embedded reinforcement that is especially critical in deep structural elements can also be weakened by such phenomena [7].

A highly fluid concrete is also prone to segregation during the mixing process, transporting, pumping, placement and also during the dormant period. Segregation can be defined as separation of granular particles from mortar, which is often associated to static sedimentation. Segregation of fresh concrete may cause several problems in concrete production and cause a non-uniform mixture [4,8,9]. Adequate stability is also critical in pumped concrete where segregation can lead to heterogeneous flow of the material in the pipeline, which could lead to blockage of the flow [10]. Furthermore, while filling the formworks, local aggregate separation and segregation may occur and the flow of the concrete across the obstacles can be blocked. This phenomenon can lead to a honeycombing concrete with non-uniform mechanical properties and durability in the hardened state and even if no heterogeneity is observed in hardened concrete surface, its mechanical properties and durability may widely vary through the cross-section. The comparison of some mixtures with a same fluidity but different levels of stability showed that although the fluidity and also compressive strength were not influenced by the stability, specimens cut from the top of hardened unstable mixtures were quite different from specimens cut from the bottom of those mixtures [5].

A proper workability, therefore, may not achieve only by increasing the concrete fluidity. Stability of fresh concrete is also an influencing parameter that should be mentioned [11,12]. There exists a relationship between fluidity and concrete stability so that an increase in the flowability of concrete would increase the risk of segregation. SCC (Self Consolidation Concrete) has been designed to satisfy these requirements.

The basic characteristics of acceptable SCC are high fluidity and adequate stability [12]. Stability, including the resistance of con-
Concrete to the separation of constituents during transport, placement, and casting process (dynamic stability) and the resistance to bleeding, segregation and settlement after casting, while the concrete is still in a plastic state (static stability) [5,10] should be provided to ensure a homogeneous SCC in the hardened state. Therefore, the mixture proportions should be properly adjusted to obtain superior deformability and high stability for the flowability of SCC through congested reinforcing bars without any heterogeneity or blockage. The fluidity of fresh SCC can be simply achieved by its water content or incorporating different chemical or mineral admixtures, but assessing its stability is more dominant. The stability of SCC is affected by numerous variables. These variables can be separated into two main categories; proportioning variables and application variables [5].

Saak et al. [13] demonstrated that increasing the yield stress and viscosity, and also reducing maximum aggregate size and specially lowering the difference in density between the aggregate and paste decrease the risk of segregation of aggregates. In fact, whereas a non-zero shear yield stress enables to avoid the initiation of segregation, the viscosity enables to limit its effects [14]. If the yield stress or viscosity is high enough, the particles will never segregate; however, the material will also have poor workability. Thus, there is a critical range of yield stress and viscosity where segregation is minimized, yet the material is self-flowing [13]. To secure the self-flowing behavior preparing several trial batches and the adjustment of mixing proportions seem to be unavoidable.

These parameters affect the fresh properties of SCC in different ways and usually improve a property while suffering another. For example, increasing W/C or superplasticizer content of a SCC mixture seems to be very effective to increase the fluidity while suffering its stability. On the other hand, VMA or additional fine graded fillers may be used for improving the stability of a SCC mixture which tends to a reduction in its fluidity in some cases. Therefore, to obtain a proper mix design of SCC mixtures the influence of various effective parameters should be respected simultaneously. The effect of several parameters such as W/C, chemical and mineral admixtures on fluidity has been reported [15–19]. However, there are only few investigations published on the effect of these parameters on the stability of SCC. Furthermore, as the behavior of hardened concrete is greatly influenced by its properties in the fresh state, much effort should carry out to investigate the rheology of SCC. This study gives a new understanding of the influencing parameters of fresh SCC properties specially its stability and homogeneity and attempts to establish proper “workability regions”. The investigated parameters include water content, superplasticizer, VMA, limestone powder and fly ash. The effect of these parameters on fluidity, viscosity and stability is reported herein. All tests are conducted on self-consolidating mortars originated from SCC. In fact, assessing the properties of mortars is an integral part of SCC design [20].

2. Experimental program

A total of 54 mortar mixtures were prepared to evaluate the influence of chemical admixtures and mineral admixtures in the yield stress, viscosity and stability of fresh mortars. Relations between the properties of concrete and corresponding mortar [15,21] are evaluated to reduce the number of concrete tests needed to evaluate the properties of SCC given a certain mix design and material proportions. Therefore, it seems reasonable to try to study the effect of water/cement ratio, superplasticizer and VMA content and different mineral additive types and contents, by only testing the mortar.

2.1. Materials

ASTM C 150 Type I ordinary portland cement was used for all the mixtures, and its chemical composition and physical properties are given in Table 1. Limestone riverbed sand with a specific gravity of 2.7, fineness modulus of 2.67 and water absorption of 2.81% was employed for all mixtures. The sand had a maximum aggregate size of 2.36 mm and particle-size distribution within the standard ASTM C33.

A polycarboxylic-based superplasticizer (SP) was used. Its solid content and specific density are 36% and 1.07, respectively. Viscosity-modifying admixture (VMA) was a polysaccharide type used as a suspension in an aqueous solution with a concentration of 20%. The mineral additives used in this study were limestone powder and fly ash. Their chemical compositions and physical properties are also summarized in Table 1.

2.2. Mixture proportions

As summarized in Fig. 1, four mortar test series were investigated. All the investigated mixtures were proportioned with a fixed cement content of 700 kg/m³ and various W/C of 0.35, 0.45, and 0.55. The amount of sand in the mixtures was varied in the range of 1250–1450 kg/m³ depending on W/C and powder content. Different dosages of SP, VMA, limestone powder, and fly ash were added in each series. The SP dosage was kept constant at 1% of binder mass for the mixtures incorporating VMA or mineral admixtures.

2.3. Specimen preparation and testing methods

Mortar mixtures were prepared in accordance with ASTM C 305 “Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency” [22]. Following mortar mixing, the flowability was evaluated by measuring the mini-slump flow and mini V-funnel flow time in conformity with the standard procedures given by EFNARC [20]. The mini-slump flow and mini V-funnel tests were selected as their results could correspond to yield stress and plastic viscosity, respectively. Indeed, it has been shown that slump flow could be related to yield stress [23–27], and the flow time could be related to plastic viscosity [25–27]. Bleeding and aggregate blockage were also evaluated during the mini-slump flow test and mini V-funnel test, respectively.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Chemical analysis and physical properties of cement, limestone powder and fly ash.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cement</td>
</tr>
<tr>
<td><strong>Chemical analysis (%)</strong></td>
<td></td>
</tr>
<tr>
<td>SiO₂</td>
<td>20.03</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>4.53</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>3.63</td>
</tr>
<tr>
<td>CaO</td>
<td>60.25</td>
</tr>
<tr>
<td>MgO</td>
<td>3.42</td>
</tr>
<tr>
<td>SO₃</td>
<td>2.23</td>
</tr>
<tr>
<td>Na₂O</td>
<td>0.25</td>
</tr>
<tr>
<td>K₂O</td>
<td>0.71</td>
</tr>
<tr>
<td>Ignition loss</td>
<td>1.37</td>
</tr>
<tr>
<td><strong>Physical properties</strong></td>
<td></td>
</tr>
<tr>
<td>Specific gravity (m²/kg)</td>
<td>3.15</td>
</tr>
<tr>
<td>Blain fineness (m²/kg)</td>
<td>290</td>
</tr>
<tr>
<td><strong>Bogue potential compound composition (%)</strong></td>
<td></td>
</tr>
<tr>
<td>C₃S</td>
<td>49.9</td>
</tr>
<tr>
<td>C₃A</td>
<td>23.5</td>
</tr>
<tr>
<td>C₅A</td>
<td>6.6</td>
</tr>
<tr>
<td>C₅AF</td>
<td>10.9</td>
</tr>
</tbody>
</table>
The static stability of the mortar was evaluated using a mini-column segregation test. The apparatus used was similar to the one described in ASTM C1610[28] but in a smaller size. It consists of a 75 mm diameter, 210 mm tall PVC pipe split into three 70 mm tall sections. Each section was clamped together to form a watertight seal. Mortar was placed into the pipe and left undisturbed for 15 min. Each section of the pipe was then removed, and the mortar inside was collected. Each mortar sample was washed over a 300 μm (#50) sieve. The retained sands were then dried and weighed. The percent static segregation was calculated as follows:

$$SI = \frac{2(\frac{\text{CA}_T}{\text{CA}_T + \text{CA}_B})}{\text{CA}_B} \times 100$$

where $SI$ = static segregation index, percent, $\text{CA}_T$ = mass of aggregate in the top section of the column, $\text{CA}_B$ = mass of aggregate in the bottom section of the column.

The acceptable segregation index for fresh concrete in most applications obtained from standard column segregation test[28] is $SI \leq 15$. However, there is not any recommended limit for mortar mixtures. Based on our experiments, mortar mixtures with $SI \leq 30$ that obtained from mini-column segregation test show satisfactory stability conditions. Mortars with a segregation index between 30–130 can exhibit segregation. Severe segregation is expected in mortar mixtures if the segregation index is above 130.

All the above tests performed twice, and the average value was reported. The test was repeated if the difference between the results was more than 20%.

3. Results and discussion

3.1. Fluidity

The results of mini-slump flow test are presented in Fig. 2. The results show that the W/C and superplasticizer content have a great influence on fluidity of the mixtures (Fig. 2a). Linear regression analysis of the results shows that increasing the W/C by about 10% can increase the mini-slump flow by about 18%. Furthermore, the addition of 1% superplasticizer, by mass of binder, can improve the fluidity of the mortar by up to 30%. In this way, the effect of 1% superplasticizer on fluidity is almost the same as 17% increment in the W/C.

Fig. 2b shows the fluidity of mortar mixtures incorporating limestone powder. The results indicate that using limestone powder may increase the fluidity of mortar mixtures. The improving effect of limestone powder on fluidity is more pronounced in lower W/C. The effect of fly ash on fluidity of mortar mixtures is also illustrated in Fig. 2c. Based upon the obtained results, using fly ash improves fluidity of mortar mixtures. The improving effect of fly ash on the fluidity may be due to its spherical shape which tends to reduce friction at the interface of aggregate and paste and producing “ball-bearing effect” at the contact point [29,30]. The effect of limestone powder and fly ash on improving fluidity is also reported by other researchers [31–33]. However, the results clearly show that the influence of these powder materials on the mixtures fluidity is much less than chemical admixtures.

On the other hand, using VMA has a deteriorating effect on fluidity. The obtained results show that using VMA up to 1.5% decreases the slump flow of the mixtures linearly (Fig. 2d). The addition of 1% VMA tends to a 30% reduction in the slump flow of the mixtures. The obtained results indicate that increasing VMA dosage greater than 1.5% does not have significant effect on the fluidity of the mixtures. Mortar mixtures with high dosages of VMA may suffer from poor rheological properties. Therefore, in that case, a higher content of superplasticizer or higher W/C should be applied in order to decrease yield stress and improve self-consolidating properties. Based on these test results, to maintain the target slump flow when 1% VMA is added, the addition of 1% superplasticizer or increasing W/C by 17% is required.

3.2. Viscosity

Fig. 3 presents the results of mini V-funnel test. As can be seen in Fig. 3a, the effect of W/C on the flow times is more dominant than the effect of superplasticizer dosage. The relationship between W/C and viscosity of the mixtures is not linear. Increasing W/C from 0.35 to 0.45 decreases the flow time by about 77%, while increasing W/C from 0.45 to 0.55 resulted in 11% reduction in the flow time.

Depicted results in Fig 3d show that the addition of fly ash also affects viscosity of the mixtures and increases it to some extent. There is not much published study on the viscosity properties of self-consolidating mortar containing fly ash, and there is not a general agreement on the effect of fly ash on the viscosity of flowable mortar mixtures.
mortars. Some authors state that incorporating fly ash in the mixtures decreases the viscosity\[31\] while some other authors report that fly ash increases the viscosity\[32\]. It seems that the difference is mainly due to the difference in types and properties of fly ash.

Obtained results clearly show that viscosity of the mixtures is mainly influenced by the W/C while the other investigated parameters have a negligible effect on the viscosity. Moreover, it is worthwhile to note that the used VMA has a negligible effect on the viscosity of cement based mixtures. This is in accordance with the report of Koehler et al.\[21\] and Sahmaran et al.\[34\] which state that there are some types of VMAs that do not significantly affect viscosity. In the next section we will focus on the effect of VMAs on stability of cement based mixtures and will show that VMA has dominant effect on the stability.

3.3. Stability

Stability of the mixtures was also evaluated by determining the segregation resistance and resistance to bleeding and risk of blockage across narrow sections.

3.3.1. Segregation and settlement of aggregates

The results of mini-column segregation test are summarized in Fig. 4. Based on these results, increasing W/C in a constant SP or increasing the SP content in a constant W/C, both, lead to an increase in segregation index of the mixtures. However, the effect of SP dosage is not linear and depends upon the W/C (Fig. 4a). For example, mixtures with a W/C of 0.35 have a segregation index less than 30% and they are all stable even if SP = 2%. On the other hand, increasing the SP content from 0% to 2% for the mixtures with a W/C of 0.55 changes a very stable mixture (SI = 20%) to an unstable mixture (SI = 158%).

Moreover, using VMA seems to be very effective in enhancing segregation resistance of the mixtures. The effect of VMA on stabilizing cementitious mixtures seems to be more dominant at higher W/C. For example, the addition of VMA by 1% of cement mass in the mixtures with a W/C of 0.55, led to a decrease in segregation index from 159% to 83%. However, all the mixtures containing more than 1.7% VMA have a segregation index less than 30% and are very stable (Fig. 4b). It should be mentioned that using VMA decreases the fluidity of the mixtures which necessitates greater
SP or W/C to maintain the target fluidity. Fig. 4c and d indicate that the effect of W/C on the aggregate segregation is more important than limestone content and fly ash content. However, increasing the powder content, slightly increase the risk of segregation.

Fluidity of the mixtures may be achieved either by the addition of superplasticizer or increasing the W/C. However, the increased fluidity may cause instability. The relationship between fluidity and segregation index for the mixtures with variable dosages of SP and W/C is shown in Fig. 5. The solid line shows the mixtures in which the W/C was kept constant and the fluidity was increased by the addition of SP. On the other side, the dashed line shows the mixtures with constant SP and variable W/C. It is clearly evident that the slope of solid lines is much lower than those of dashed lines. This means that the SP increment is preferable over W/C increment for achieving the required fluidity since it will result in more stable mixtures.

Based on these results, the most significant parameter influencing aggregate segregation is the W/C. Fig. 6 shows the segregation index versus W/C of the mixtures. As can be seen in the figure, mortar mixtures with a W/C of 0.35 are stable in all the cases. On the other hand, mixtures with a W/C of 0.55 often exhibit severe segregation. Some SCC guidelines [32] define a certain limit for W/C to avoid segregation. The results reported herein indicate that the maximum acceptable W/C is not a fixed value and is a function of the fluidity level of the mixtures. For example, when the fluidity is less than 20 cm, mixtures are stable in all W/C. For the fluidity of 25 cm, there seems to be a threshold value of W/C (W/C = 0.46) beyond which segregation index is greater than 30% and aggregate segregation may occur. On the other hand, all the mixtures with a fluidity equal or more than 35 cm have a stability index above 30% and instability may occur in all the cases. In order to prevent mortar instability, EFNARC has limited the target slump flow to 26 cm [20], but the obtained results indicate that fluidity of the mixtures can be adjusted based upon the selected W/C.

3.3.2. Bleeding and blockage of aggregate

Bleeding and blockage of the aggregates are evaluated indirectly in the mini-slump flow test and mini V-funnel test. Bleeding of the mixtures is summarized in Fig. 7. As shown in the figure, increasing the W/C or SP content, especially at higher W/C, both, lead to an increase in bleeding of the mixtures. However, the comparison of Figs. 2a and 4a indicates that for a constant fluidity, mixtures with a lower W/C and higher SP dosage seem to exhibit less signs of instability. On the other hand, by using VMA, limestone powder
or fly ash, even at low dosages, bleeding of the mixtures was completely disappeared. For example, in the case of W/C of 0.55, the addition of only 0.5% VMA by cement mass resulted in a decrease in the mixtures bleeding from 9 cm to 0 cm. In a similar way, no
bleeding was observed in the mixtures incorporating 10% limestone powder or fly ash.

Blockage of the mixtures is presented in Fig. 8. As shown in the figure, mixtures with higher W/C are prone to aggregate blockage while flowing narrow section of mini V-funnel nozzle. The obtained results indicate that using limestone powder or fly ash and also applying VMA, even at low dosages, could be very effective in enhancing flow properties of cementitious mixtures and prevent aggregate blockage while flowing across narrow sections. Therefore, for preventing bleeding and aggregate blockage of cementitious mixtures reducing W/C or using VMAs, limestone powder or fly ash could be suggested.

The obtained results in this study also indicate that using VMAs is a very effective and efficient way for preventing any types of instability, including segregation, bleeding or blockage of the aggregates while using limestone powder or fly ash only improve the mixtures resistance to bleeding or aggregate blockage.

3.4. Relationship between fluidity, viscosity and stability

The similarity of Fig. 2 with Fig. 4 indicates that there exists a close relationship between fluidity and stability of the mixtures. As the former increases, the latter greatly decreases. However, a proper self-consolidating concrete should exhibit high fluidity and stability characteristics simultaneously. To reach a stable highly flowable mixture, the adjustment of mixture proportions and obtaining the optimum values of fluidity and viscosity are necessary. The relationship between segregation index and fluidity of the mixtures is plotted in Fig. 9. As the fluidity increases, the segregation index increases exponentially. Khayat and Assaad [35] also reported that exponentially response can be observed between stability and fluidity of SCC. In spite of very simple test method used in this study and carrying out the tests on the mortars, the similarity of the observed trends indicates that these test methods can be very effective for evaluating the properties of fresh concrete.

Fig. 9 divided into four regions. Mixtures in the first region (mixtures with fluidity greater than 24 cm and segregation index less than 30%) correspond to stable and highly flowable mixtures. Mixtures in the second region exhibit high segregation resistance while suffering from poor fluidity. These mixtures do not have sufficient fluidity to flow readily under their own weight. To increase the fluidity of these mixtures, the higher W/C or SP dosages should be applied. For example, in Fig. 9, point 1 (W/C of 0.4 and no SP dosage) corresponds to the fluidity of 12 cm and segregation index of 6%. An alternative for increasing the fluidity to 30 cm is to use

Fig. 7. Bleeding of the mixtures.
1.5% superplasticizer. By this method, segregation index will be equal to 33% (point 2) that indicates a relatively stable mixture. By increasing W/C up to 0.55 and using 0.35% superplasticizer the target fluidity may also be provided (point 3). This increases the segregation index up to 95% and resulted in a mixture which is more prone to segregation. Based on these results, for obtaining high fluidity, increasing the W/C should not be applied due to instability aspects. Moreover, higher W/C may, also, lead to poor mechanical behavior of hardened concrete. So it is more efficient to apply higher SP dosages for obtaining super fluidity of the mixtures. When the lack of fluidity is not too much, the use of lime-stone powder or fly ash may be also effective.

Mixtures in the third region are highly fluid while suspecting to instability and segregation. Using VMAs is a very effective tool for improving the stability of such mixtures. But it should be noticed that the use of VMAs may decrease the fluidity of the mixture and an increase in SP content is necessary for retrieving the initial fluidity. The obtained results indicate that increasing the W/C may compensate the stabilizing effect of VMAs, so it is not recommended to increase W/C to regain the reduced fluidity. The use of VMAs may lead to mixtures with low fluidity and addition of
prepared to investigate the effects of different parameters on the adjustment of these parameters. In total, 54 mortar mixtures were way to achieve self-compacting characteristics is the correct rheological behavior of SCC in different manners and the only of the mixtures should be exactly studied. These parameters affect characteristics may exhibit various stability properties due to different mixture proportions.

Three stability response workability regions are defined in Fig. 10 as a function of fluidity and viscosity. These regions correspond to segregation index ranging less than 30%, between 30% and 130% and greater than 130%. The fluidity of mixtures in the first region (stable mixtures) is lower than 30 cm while mixtures in the third region (unstable mixtures) exhibiting the fluidity greater than 30 cm and flow time lower than 5 s. Based on these results, neither the fluidity less than 30 cm nor the flow time lower than 5 s, by itself, can ensure the stable mixture. On the other hand, mixtures with a flow time greater than 10 s may suffer from, both, poor fluidity and segregation resistance. The proportion of these mixtures’ ingredients should be properly adjusted due to the previous explanations.

Three stability response workability regions are defined in Fig. 10 as a function of fluidity and viscosity. These regions correspond to segregation index ranging less than 30%, between 30% and 130% and greater than 130%. The fluidity of mixtures in the first region (stable mixtures) is lower than 30 cm while mixtures in the third region (unstable mixtures) exhibiting the fluidity greater than 30 cm and flow time lower than 5 s. Based on these results, neither the fluidity less than 30 cm nor the flow time lower than 5 s, by itself, can ensure the stable mixture. On the other hand, mixtures with a flow time greater than 10 s may suffer from poor workability. There are also some intersection regions observed in Fig. 10 which indicate that mixtures with the same flowability and superplasticizer content cannot be controlled adequately or in mixtures with poorly graded aggregates or low powder content. Mixtures in the fourth region may suffer from, both, poor fluidity and segregation resistance. The proportion of these mixtures’ ingredients should be properly adjusted due to the previous explanations.

4. Conclusions

To obtain a proper SCC with super workability, the effect of different concrete ingredients including W/C, type and dosage of chemical and mineral admixtures on the fluidity and also stability of the mixtures should be exactly studied. These parameters affect the rheological behavior of SCC in different manners and the only way to achieve self-compacting characteristics is the correct adjustment of these parameters. In total, 54 mortar mixtures were prepared to investigate the effects of different parameters on the rheological properties of cementitious mixtures. Based on the results of this study, the following conclusions can be made:

- The most significant parameters affecting mixtures fluidity are the W/C and superplasticizer content. The use of limestone powder and fly ash also improves fluidity to some extent. On the other hand, the use of VMA can decrease fluidity.
- The effect of W/C on the viscosity of mixtures is more dominant than other studied parameters. The W/C affects viscosity exponentially such that increasing W/C up to 0.45 strongly decreases the viscosity. Furthermore, using fly ash increases viscosity, but other parameters did not significantly influence the viscosity.
- The increase in fluidity of the mixtures tends to have a significant reduction in the stability. To minimize the unpleasant effects of high fluidity on the stability, addition of superplasticizer instead of increasing W/C is suggested. Based on the obtained results, in a constant W/C, increasing the mini-slump flow by one centimeter tends to increase segregation index by an average of 2.6%. For a constant superplasticizer content, using higher W/C to increase mini-slump flow by one centimeter can result in an increase in segregation index by about 7.5%.
- The W/C is the most significant parameter influencing rheological parameters of cementitious mixtures. Higher W/C tends to inhomogeneous mixtures, while reducing the viscosity.
- Maximum allowable W/C of a cementitious mixture for preventing heterogeneity mainly depends on the target fluidity. A mortar mixture with mini-slump flow less than 20 cm is stable in all of the investigated W/C. For a mini-slump flow of 25 cm, W/C should limited to 0.46. On the other hand, all the mixtures with a mini-slump flow greater than 35 cm are prone to severe segregation.
- Using VMAs is a very effective tool of stabilizing self-consolidating mortar and preventing bleeding, segregation and blockage of flow through narrow sections, while limestone powder and fly ash are shown to be only effective in reducing bleeding and aggregate blockage.

Acknowledgements

This work was financially supported by Construction Materials Institute (CMI), faculty of Civil Engineering, University of Tehran. The authors would also like to express their gratitude to Prof. Khayat for his advice and comments. The authors are also thankful to Miss Shirin Jawhari Moghadam for contributing in the work.

References


